Modeling the Performance of Optical Refrigerators

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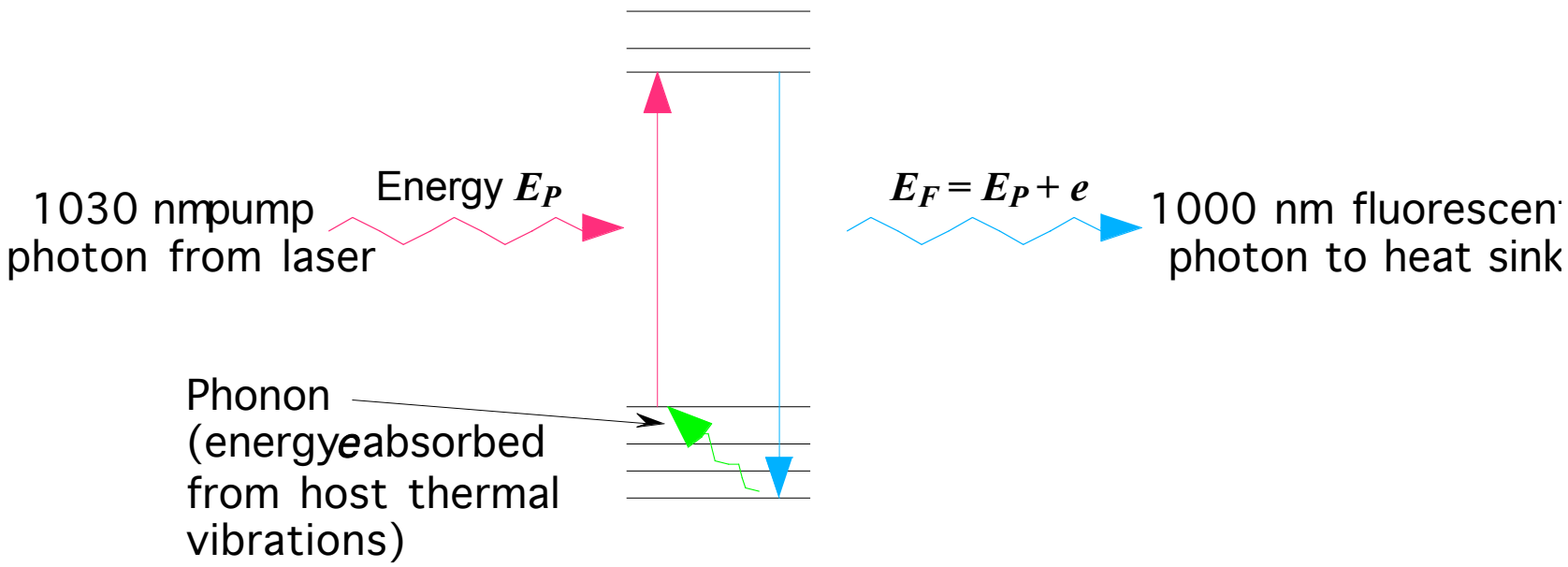
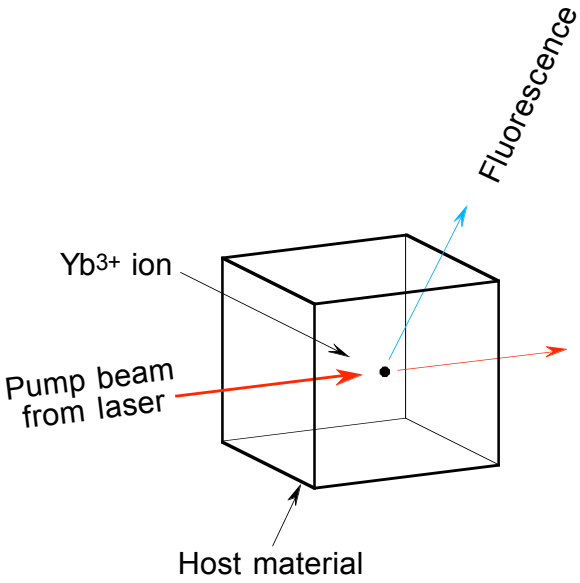
Earth Science Technology Conference
June 28-30, 2005
Adelphi, MD

The Photon-Phonon Refrigeration Cycle



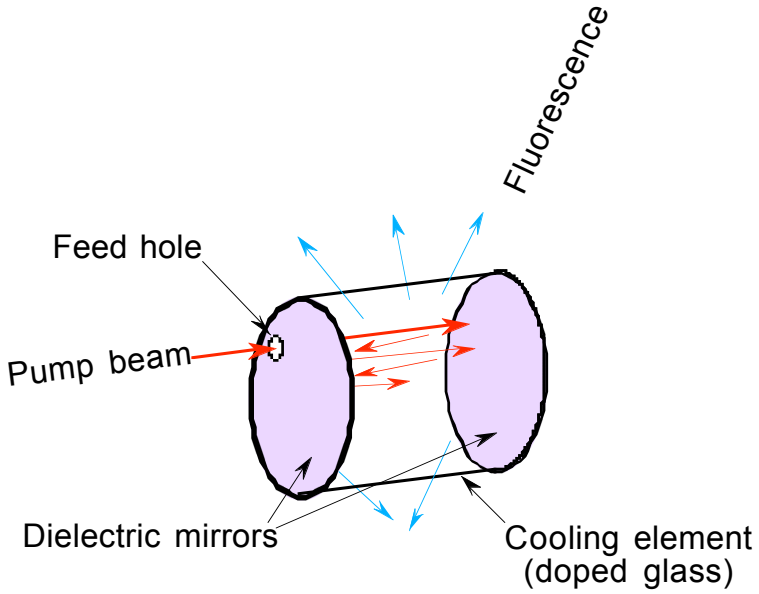
Energy levels of Yb^{3+} ion in ZBLAN glass host

Optical Cooling Process:
Optical Pump Photons Remove Heat Phonons

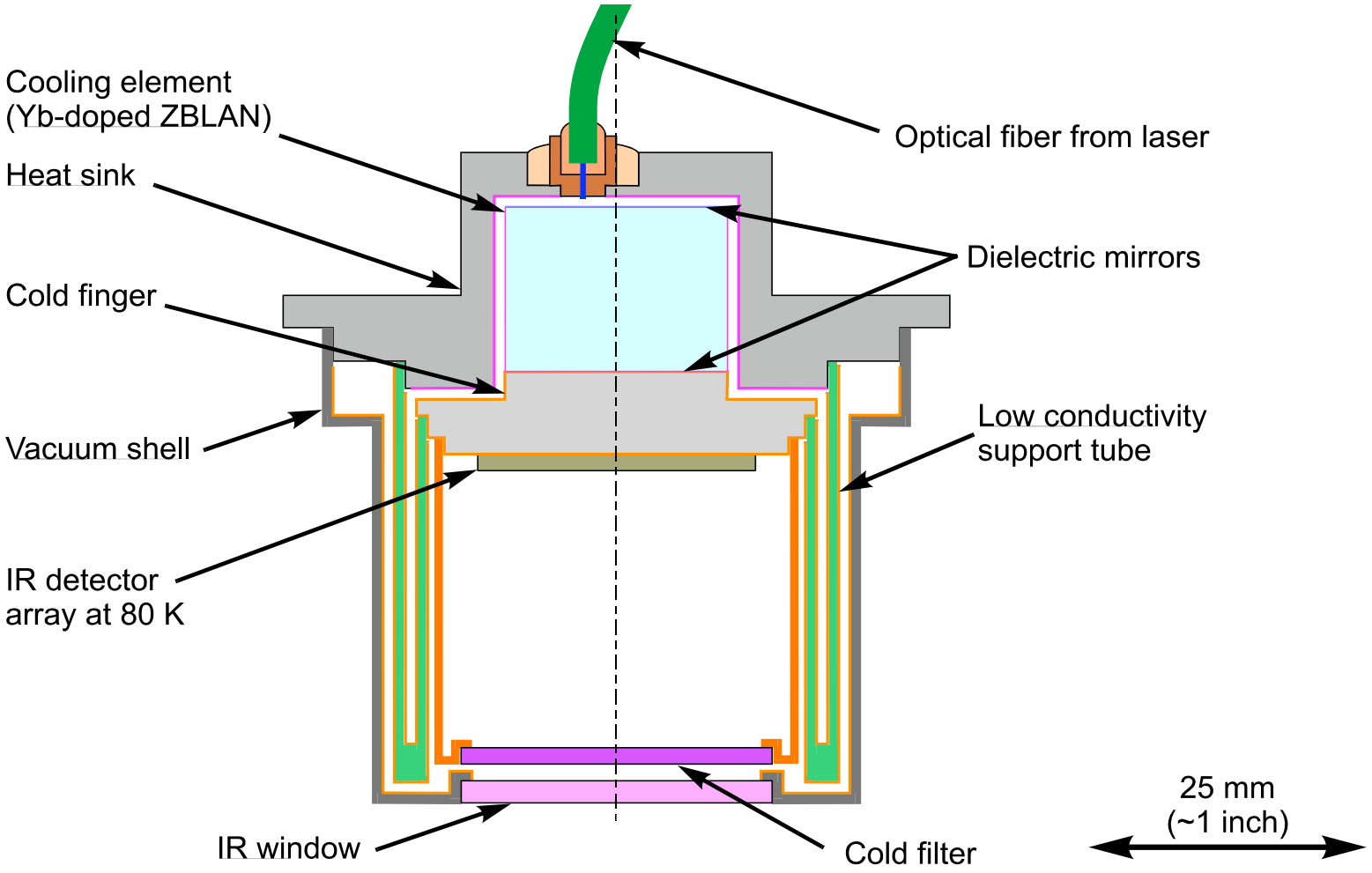


- **Pump photon absorbed by Yb dopant atom**
- **Photon re-emitted slightly bluer (higher energy)**
- **Energy difference comes from thermal vibrations (phonons) of host material**

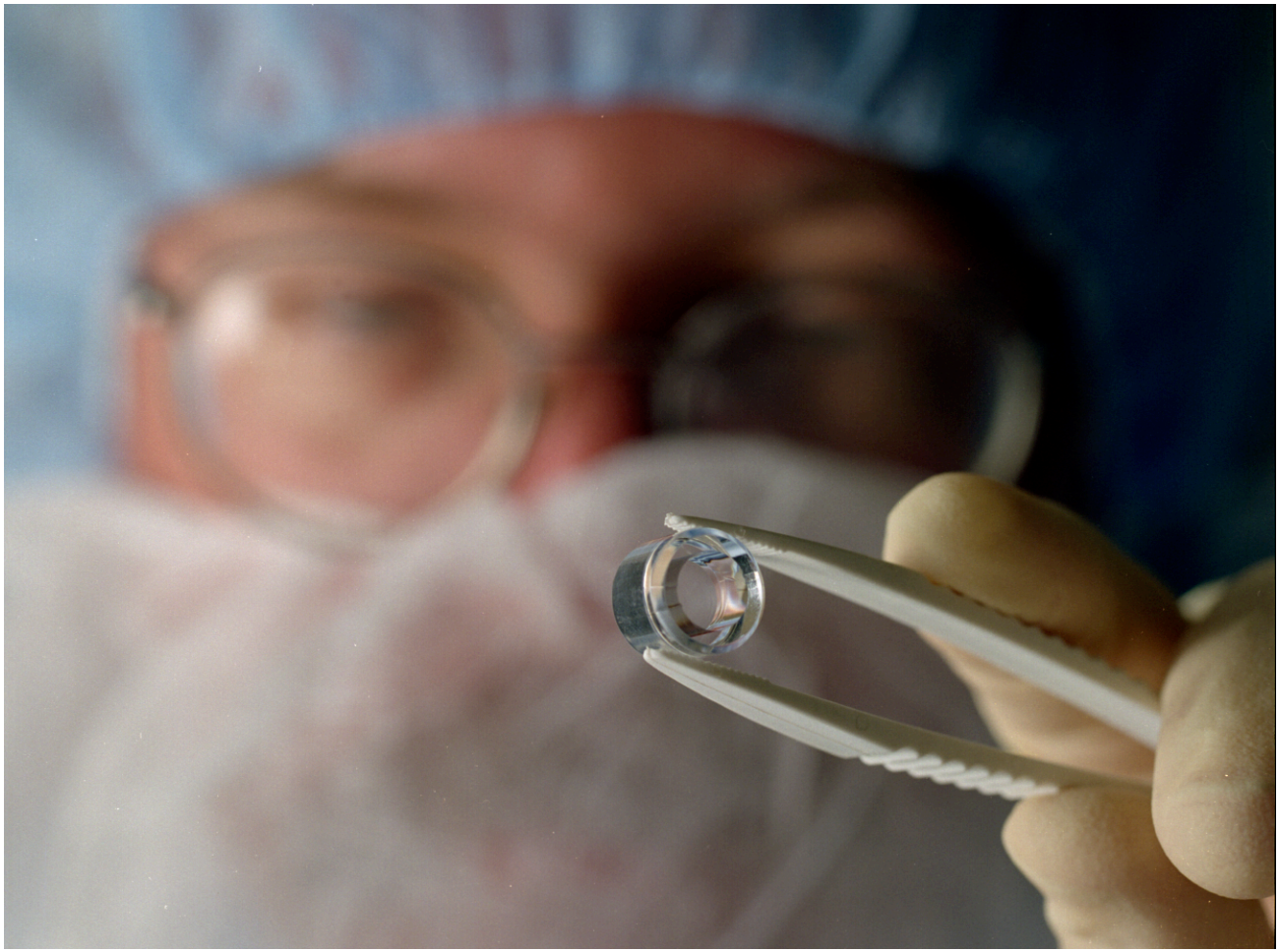
- **High-reflectivity mirrors provide long path length for pump beam**
- **Fluorescence escapes from uncoated sides of cooling element**



Simplified Design of Compact IR Detector / Cryocooler Package Capable of Lifting 400 mW at 80 Kelvin



Fluorescent element is Yb doped Zirconium Flouride glass (ZBLAN)



Comparison to other Cryocooler Technologies is Favorable in Many Areas

- **Vibration**
  - Optical cryocooler is solid state; zero vibration is an obvious advantage
- **Electromagnetic and magnetic noise**
  - Optical cold head uses only photons, no electrons: no noise
  - Laser can be remotely located to minimize noise; split Stirling machines can have remotely located compressors, but with significant drawbacks
- **Reliability and lifetime**
  - No moving parts, laser is the life limiting component
  - Solid state lasers are made up of many diodes whose output is joined together by optical "Y" junctions
  - Laser diode modules have lifetimes of several years with a Gaussian lifetime distribution
  - Redundancy is inherent; more can be added with no impact on thermal performance

Comparison to other Cryocooler Technologies is Favorable in Many Areas (continued)

- **Extreme environments**
  - The glass cooling element is separated from the heat sink by a gap; it is inherently protected from physical stress
  - Glass cooling element has a compact form factor that withstand high accelerations
  - High temperature environment: fluorescent cooling process is not directly affected by temperature of the heat sink.

- **Miniaturization**
  - Complete cryocooler with less than 1 cm^3 volume appears possible.
  - Sub-millimeter diode lasers already exist

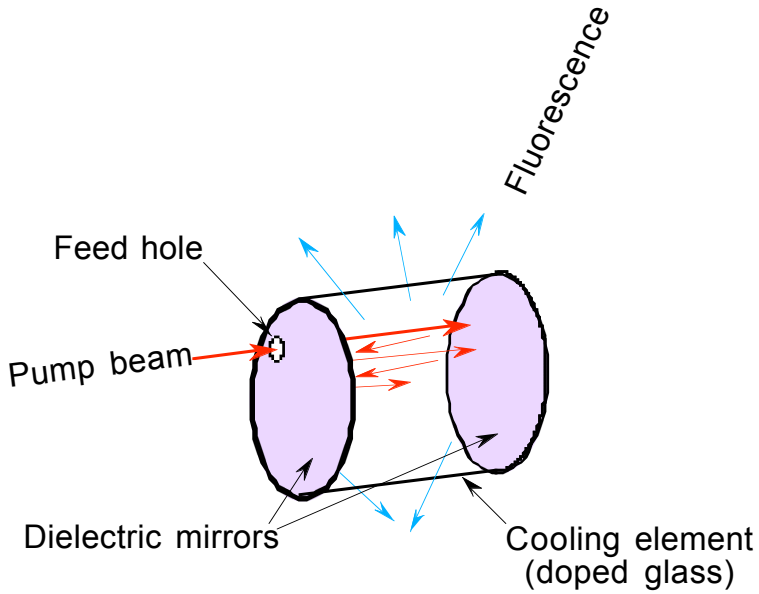
- **Cost**
  - Technology used permits low-cost manufacture
  - No high-precision mechanical assemblies
  - Material and process issues are all ones that have been worked out for high-volume industries

Technology Readiness Assessment Shows History, Current Status and Development Direction of Technology

- TRL 1: *Basic Principles Observed and Reported*
  - LANL in 1995: Less than 1 °C cooling observed in isolated glass
- TRL 2: *Technology Concept Formulated*
  - LANL and Ball 1996 to 1998: Achieve 50 °C cooling in isolated glass
  - Ball in 1999: System design study based on LANL data concludes it is a feasible technology for cooling small devices
- TRL 3: *Technology Critical Function & Proof of Concept* ← *Today*
  - Ball-NASA ATIP program discovered and solved mirror leakage problem; allowing a load to be cooled
  - Load cooled 15.6 °C with 145 watt/watt specific power
  - Photon recycling with photocells may increase overall efficiency 5 X
  - LANL has cooled an isolated fluorescent element to 208 K
- TRL 4: *Concept-Enabling Level of Performance*
  - Will require cooling a load 150 °C (to 150 K) and < 35 watt/watt to be competitive with multi-stage thermoelectrics
- TRL 5: *Breadboard in Relevant Environment*
  - Should come quickly after TRL 4 achieved

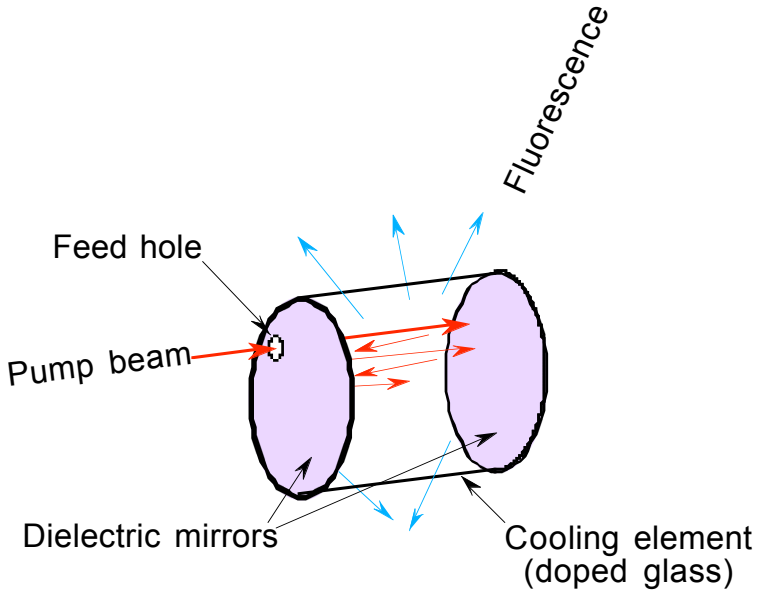
Optical Refrigerator Model

- **Tracing the life history of the incoming pump photons**
- **Tracing the life history of the outgoing fluorescent photons**
- **Evaluating the internal and external heat transfer**



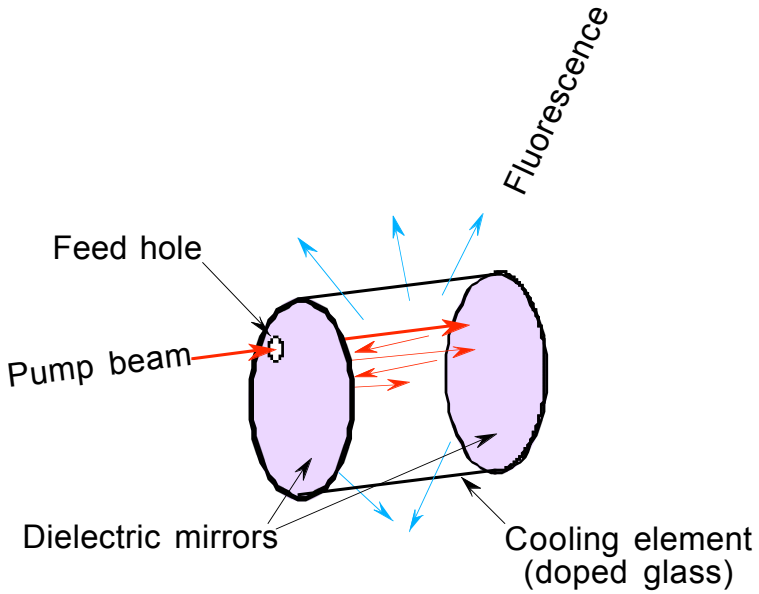
Tracing the life history of the incoming pump photons

1) Absorption by Yb, which includes the reduction by saturation at high power densities.,
2) Absorption by anything else, including unknown contaminants that can only be described empirically,
3) Leakage out through mirrors,
4) Leakage out through feed hole, and
5) Leakage out through imperfect mirror edges

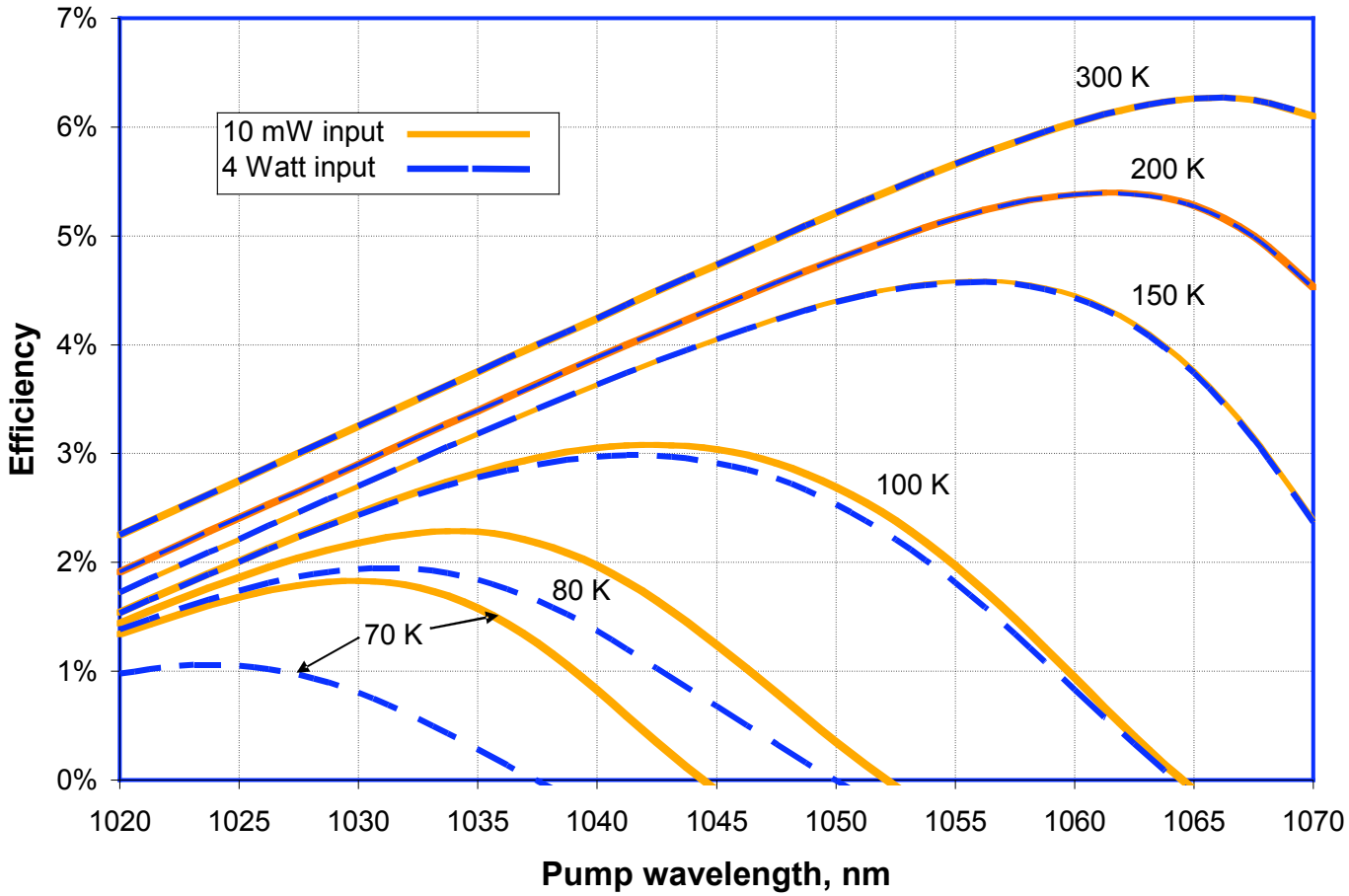


Tracing the life history of the outgoing fluorescent photons, the possible fates

1) **Escape through the end mirrors (as much as 27%)**
2) **Escape through the sides**
3) **Re-absorption by Yb (recycling)**
4) **Absorption by anything else, which is assumed to cause heating**

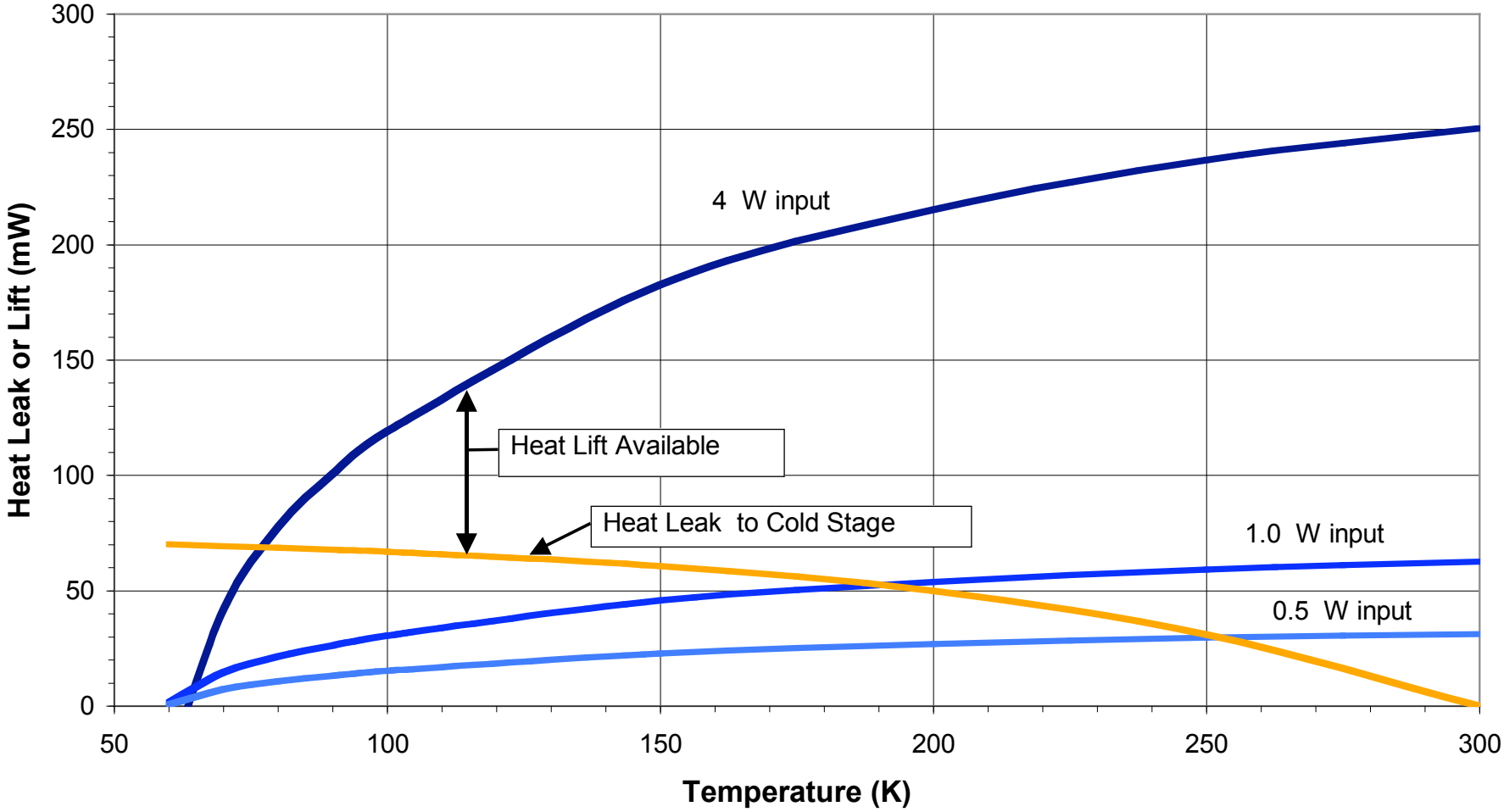


Photon Model Results for 2% Yb:ZBLAN Fluorescent Element, 15 x 7 x 7 mm



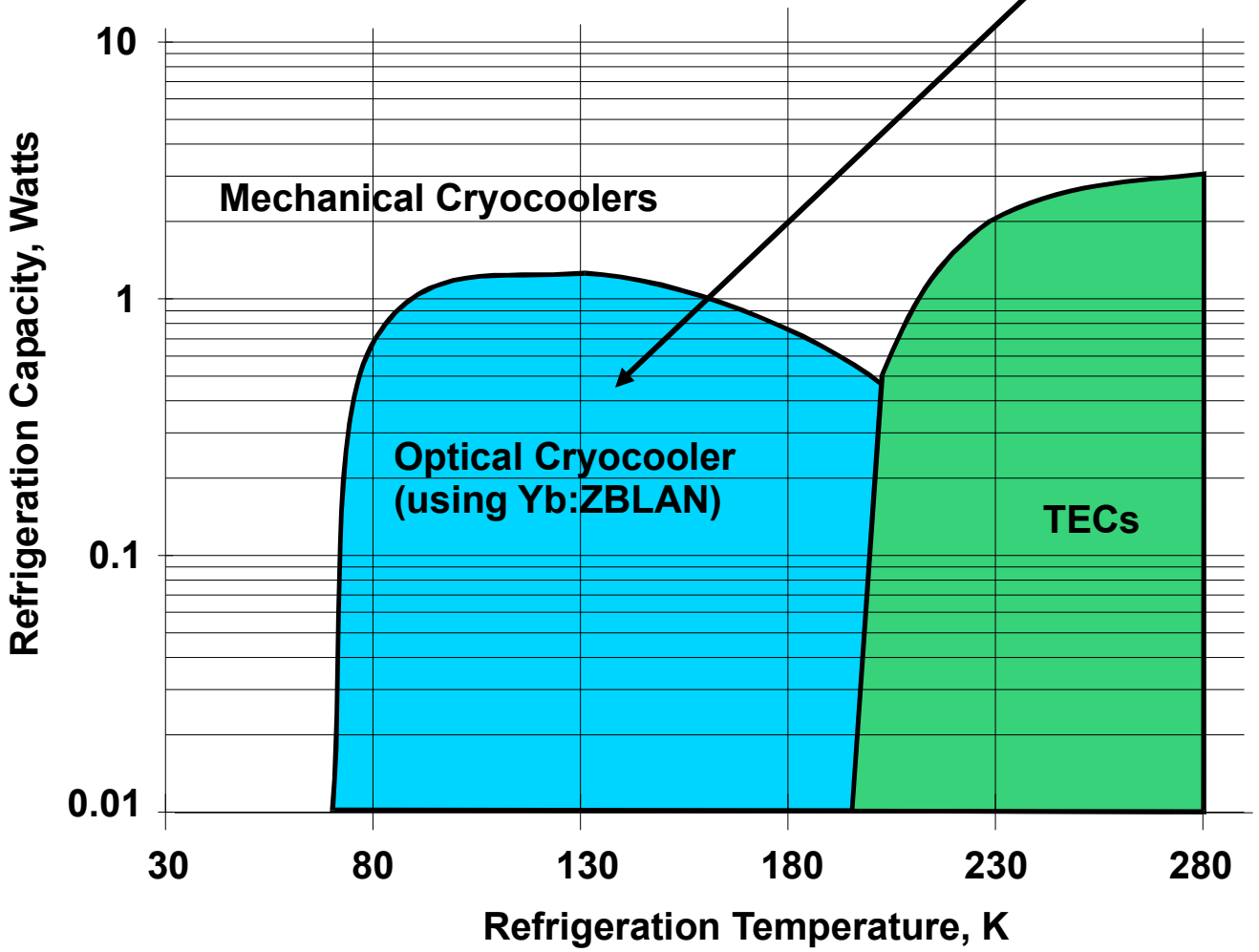
- Efficiency drops with T due to Boltzmann distribution
- Optimum λ for at given T because of $\Delta\lambda$ vs. absorption length
- At lower T, power saturation effects become significant

Performance of Refrigerator with 2% Yb:ZBLAN Fluorescent Element, 15 x 7 x 7 mm



- **Heat leak calculated from thermal model and is independent of lift**
- **Available heat lift is difference between lift and leak**

Optical Cryocooling has the Lowest Spacecraft System Mass in this Region



The Challenge of Cryogenics on a Small Scale

- Workshop sponsored by Dr. Clark Nguyen of DARPA on micro cryocooling held in July 2003 explored possibility of cryocoolers with a total volume of 2 cm^3 and less than 100 mW power draw.

- "The Navy's use of cryogenic devices would increase if they had less impact, such as being small enough to fit on VMX circuit card like any other component." - Navy consultant in at M-CALC IV cryocooler conference, Nov. 2003

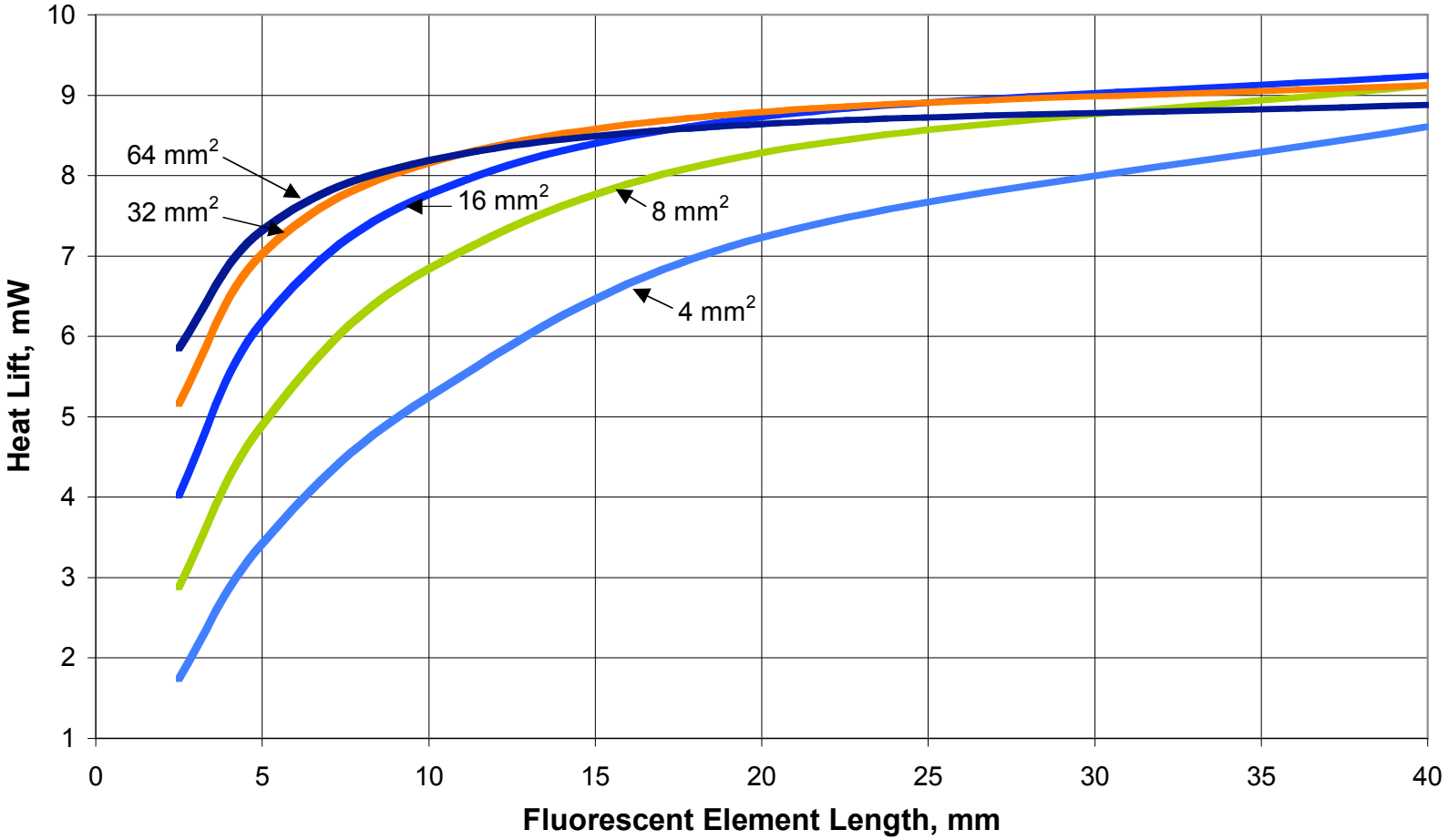
- January 2005: DARPA releases Broad Area Announcement (BAA) 05-15, "Micro Cryogenic Coolers" which solicits development of small cryogenic systems based on:
  - MEMS fabrication
  - Targeted cooling
  - Miniaturization of cooled device and cryocooler

- BAA 05-15 goal: cooled device and cryocooler with a …
  - Volume of less than 4 cubic centimeters
  - Power draw of less than 100 mW

Our Answer: An Entire Cryogenic System with a Volume of 3.0 Cubic Centimeters

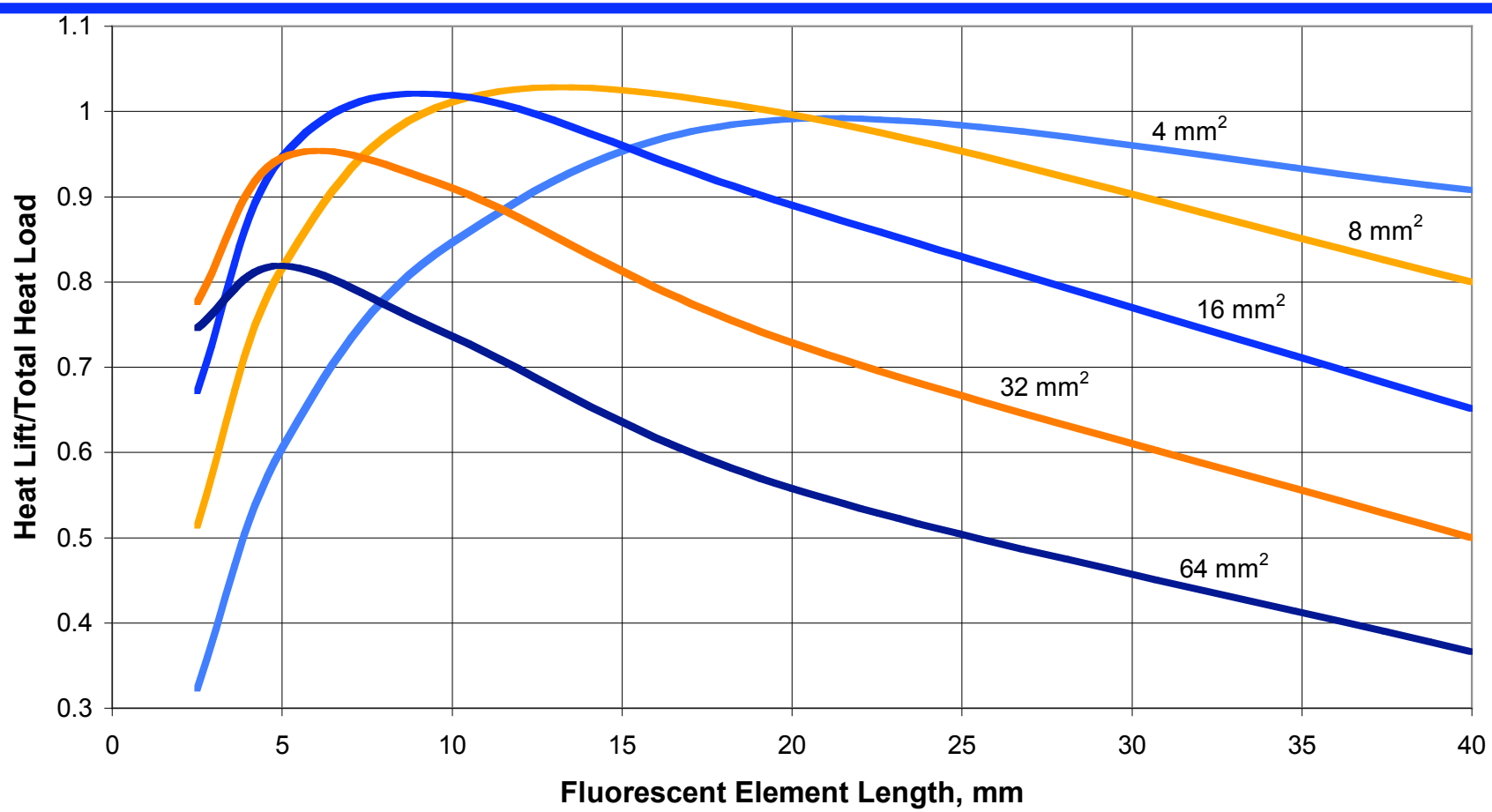
- **Artist's rendering of a micro cryostat containing:**
  - A transition edge bolometer operating at 90 K
  - Yb:ZBLAN fluorescent element
  - A diode laser
  - Vacuum insulation
- **Terahertz antenna mounted on outside.**
- **Applications include:**
  - Non-destructive imaging and inspection through normally opaque materials
  - Detection and identification of chemical compounds
- **Micro cryostat could accommodate other small cryogenic devices such as superconducting filters or amplifiers**
- **Size, volume, power < 10 X less than current S. O. A.**

Heat Lift of 2% Yb: ZBLAN Fluorescent Element Pumped with 300 mW and 1035 nm



- **Increasing length increases efficiency and heat lift; pass loss reduced**
- **Increasing cross section decreases saturation but also increases reabsorption and "reddening" of the fluorescence**

Radiative heat load on fluorescent element results in optimum configuration for 300 mW input



- **Total heat load includes 5 mW from application device and interface device at 90 Kelvin operating temperature**
- **Optimum occurs at 10 mm length and 3 to 4 mm width**

Conclusions

- We have developed a comprehensive model of the photon and thermal process of optical refrigerators.
- Model is very useful in guiding design
  - Optimizing wavelength
  - Optimizing fluorescent element geometry
  - Yb:ZBLAN fluorescent elements are not practical at lengths less than 5 mm
  - Optical refrigeration using Yb:ZBLAN can meet DARPA volume goal
- Possible follow-on work
  - Extend model to cooling materials other than Yb:ZBLAN
  - Model crystalline materials with non-isotropic absorption and emission